EXHIBIT B

IN THE DISTRICT COURT OF THE UNITED STATES

FOR THE EASTERN DISTRICT OF MICHIGAN

BILLINGS DIVISION

UNITED STATES FIDELITY AND GUARANTY COMPANY,

Plaintiff,

and

Case No. CV-04-29-BLG-RFC

CONTINENTAL INSURANCE COMPANY,

Plaintiff Intervenor,

vs.

SOCO WEST INC.,

Defendant.

The Deposition of BRUCE E. DALE, Ph.D.,

Taken at 300 Mac, Marriott Hotel,

Lansing, Michigan,

Commencing at 8:57 a.m.,

Monday, October 5, 2009,

Before Kathryn L. Janes, CSR-3442, RMR, RPR.

COPY

Page 38

discharges of perc and perc-containing wastes?
MR. DAVIS: I object to the form.
Do you understand the question?
MR. GROSSBART: Are you talking about in the context of that sentence?
BY MR. LYNCH:
Q. In the context of that sentence, what's the distinction between a spill, leak or other discharge?
A. How do I distinguish between spills, leaks and other discharges --
Q. Yeah.
A. -- in my mind? A spill usually involves a human involvement, some human is involved. A leak, equipment may or may not leak with or without human involvement. And other discharges, anything else that might happen. It's to cover the breadth of the kind of releases that can occur.
Q. If you go to the pages 9 and 10 in your report, and there you have a listing of prior expert testimony you've given.
A. Yes, that's right.
Q. Am I correct that other than number 14, which is the instant case, the subject of your testimony where it has involved a spill, leak or other discharge of perc, has always been in connection with contamination

Page 39

resulting from dry cleaning operations?
A. That's correct.
Q. What types of discharges were involved?
MR. GROSSBART: Are you talking about these other cases he worked on?
MR. LYNCH: Yes.
A. What kind of spills, leaks or other discharges occur, of perc occurred in dry cleaning operations?
BY MR. LYNCH:
Q. In the cases that you've actually worked on?
A. Well, the breadth of possibilities. I don't know how to answer your question more directly than that.
MR. GROSSBART: Are you asking about the factual circumstances?
MR. LYNCH: Let me see if I can clarify.
MR. DAVIS: How about this for short circuiting, you did ask him about those questions, that topic in a December 2005 deposition he gave in this case, and while I can't imagine that he recalls verbatim, I think you explored it in great detail, and you might ask him if he's aware of any facts that would cause him to change any testimony he gave about those other cases four years ago.
BY MR. LYNCH:
Q. I would like to know, though, sitting here today, and

Page 40

maybe we can short circuit this, did any of the other cases you were working on deal with allegations of a one-time spill of perc onto -- deal with a one-time spill of perc in excess of 50 gallons?
A. Yes.
Q. Okay. And do you know which cases?
A. First case, Houston General Insurance versus Texas Industrial Services.
Q. And how large was the spill of perc --
A. The alleged spill --
Q. -- in that case?
A. The alleged spill was around 200 gallons, if I recall correctly.
Q. And how was it alleged to have occurred?
A. During a fire at an industrial dry cleaning facility.
Q. And what was the surface it was alleged to have spilled on?
A. Concrete.
Q. Any other of those cases in which you've dealt with that deal with an alleged one-time spill of perc in excess of 50 gallons?
A. As far as I can recall sitting here, no.
Q. Have you ever seen a spill of perc onto an asphalt surface, a spill of greater than 10 gallons of perc onto an asphalt surface?

Page 41

A. No, I have not.
Q. Have you ever seen a spill of perc onto an asphalt paved surface?
MR. GROSSBART: What's the difference between those two questions, the gallon amount?
BY MR. LYNCH:
Q. Of any amount?
A. Would you want to define spill, what --
Q. Well, as you use it, and you've made an intensive study of spills, something...
A. Have I seen pictures? Have I been there physically myself to witness it? I'm not sure what you mean by seen it.
Q. All right. Have you seen any pictures?
A. Yes, I have.
Q. And what did you see those pictures in connection with, is that in connection with one of the cases you've worked on?
A. Yes.
Q. Do you know which case?
A. Well, it wasn't any one of these cases, it was in connection with a case. A friend of mine -- can I give you a narrative answer to be quick?
Q. Sure, sure.
A. A friend of mine, Mr. Eldon Dickinson, who lives here

Page 50

MR. LYNCH: Yes.
MR. GROSSBART: -- on asphalt?
MR. LYNCH: Yes.
MR. GROSSBART: Okay.
A. **In the areas where there had been a flow of perc over asphalt, that asphalt would look whiter. The aggregate would be exposed. You would see the color of the underlying aggregate which is generally lighter in color than the asphalt. The areas where perc and asphalt that had been dissolved from the perc pooled would look like a dark tar pit. It would be a dark tarry mass as I described it.**
Depending on the velocity of the discharge of the perc, there could have been holes dug in the asphalt as the perc essentially blasted its way into the asphalt dissolving some of the asphalt and moving some of the gravel.
BY MR. LYNCH:
Q. Any idea what type of velocity it would be -- would be necessary to create that phenomena?
MR. GROSSBART: Objection to the incomplete nature of the hypothetical, over what period of time. You've got to ask him proper hypotheticals. This is not one. I've yet to hear one.
A. **If you can provide me more.**

Page 51

BY MR. LYNCH:
Q. Well, you said it could occur, but under what conditions could it occur?
MR. DAVIS: I think he just described it.
A. **If a stream of perc contacts the asphalt with some velocity, over time it will tend to dig a hole there.**
BY MR. LYNCH:
Q. And you said some velocity, I'm asking what type of velocity?
A. **Any -- any type of velocity. It would have been a time and velocity.**
Q. Perc flowing in 60 gallons a minute out of a 2-inch hose for four minutes onto an asphalt surface, is that going to have that effect?
A. **Probably so if it's on one area, if it's focused on one spot.**
Q. What's your basis for that opinion?
A. **Perc leaving a hose, a 2-inch hose 60 gallons per minute is traveling about 12 to 13 miles per hour, that's magnified by the density of perc being greater than water, so it's hitting that with the water equivalent of water traveling about 20 miles per hour, except this stuff dissolves asphalt, so there's a lot of force involved.**
Q. How do you calculate how quickly it's traveling, the

Page 52

perc out of the hose?
A. **If it's traveling -- if it's being discharged according to your hypothetical, at 60 gallons per minute from a 2-inch outer diameter hose, the inside diameter is about 1-and-a-half inches and it's a simple calculation of mass flow, the area through which it's traveling divided by the volumetric flow gives you the velocity.**
Q. Have you performed that calculation in connection with your opinions?
A. **Yes.**
Q. Okay.
MR. DAVIS: He just did.
BY MR. LYNCH:
Q. Did you just perform that calculation in your head based on --
A. **No, I didn't.**
Q. So that's something you previously performed --
A. **Yes.**
Q. -- in connection with your opinions?
MR. LYNCH: We would like to see that calculation.
MR. GROSSBART: I don't know what he's referring to. I'll discuss it with him at a break.
Is that an equation you could set out on a

Page 53

piece of paper here, Bruce?
THE WITNESS: Sure.
MR. GROSSBART: Why don't you just --
MR. LYNCH: We can do it during a break.
MR. DAVIS: Yeah, I don't know that he's preserved it.
A. **It's an easy calculation, but...**
BY MR. LYNCH:
Q. Maybe during the next break if you could just lay out the calculation we could have it?
A. **Sure.**
Q. Without knowing all of the variables and conditions that surround this spill, is there any way of further characterizing or quantifying the degree of discoloration that would occur?
A. **No.**
Q. I believe you said areas over which perc flowed would be lighter, can you provide any more quantification or description of how much lighter they would have been?
A. **No.**
Q. Could there have been a minimal lightening of the asphalt?
MR. GROSSBART: Objection to the subjective nature of the use of the adjective minimal.
A. **I don't know what you mean by minimal.**

Page 58

allow me to answer with any degree of precision. I would need to know since it's the temperature, clean-up efforts, how fast the discharge occurred, over what area. There's just too many -- too many variables that you haven't specified.
Q. Did you make any assumptions as to any of those opinions in connection with your opinion?
A. No.
Q. Let's move on actually to opinion 2A, actually, strike that. Let me just go back briefly to opinion 1. The, after the first sentence, you indicate, you state: Such evidence includes and then go on to list points A, B, C and D certain physical evidence that in your opinion would result. Is there any other types of physical evidence that in your opinion would result from the large spill of the type alleged in this litigation?
A. I think these are the obvious ones.
Q. Now let's move on to opinion 2A. First sentence states: Given the density and viscosity of perc, a release of 250 gallons of perc onto an intact, level surface with which perc did not interact, would spread to a circle about 48 feet in diameter; did I read that correctly?
A. Yes.

Page 59

Q. That opinion, am I correct, is based on a mathematical calculation that you've done previously in this litigation?
A. Yes. And actually we're not going to mark these. They have already been previously marked as deposition exhibits. Since we aren't going to mark them up, I think we will just keep the old numbers.
MR. GROSSBART: They were marked, in fact, they were marked in Grzybowski's in any event.
MR. LYNCH: Oh, they were, we can --
MR. GROSSBART: The handwritten one is 3643.
MR. LYNCH: Okay.
MR. GROSSBART: And the article is 3644.
BY MR. LYNCH:
Q. Dr. Dale, I'm showing you what's been marked, recently marked as Exhibit 3643 and 3644 in this litigation, and for the record, these documents were marked at your earlier deposition as exhibits -- Exhibit 3644 was previously marked as Exhibit 2001 and Exhibit 3643 was previously marked as Exhibit 2004.
Dr. Dale, are exhibits -- which one is the article?
MR. GROSSBART: 3644.
A. Right.

Page 60

BY MR. LYNCH:
Q. Exhibit 3644, can you tell me what that document is?
A. That's an article from Chemical Engineering Progress Magazine dated January 2005.
Q. Does that article set forth the formulas that you used to calculate the amount of spreading from a 250 gallons of perc referred to in opinion 2A?
A. Yes.
Q. Okay. If you could look at Exhibit 3643, please, and tell me what that document is?
A. That's my hand -- copy of my handwritten calculations to calculate the extent of the spill, and also evaporation rate.
Q. And maybe if we could just go through this document so I'm clear, on Exhibit 3643, you have -- list under calculations, which is underlined, you have, it says assume 250-gallon spill and 77-degree Fahrenheit ground temp and air temp?
A. That's correct.
Q. Are those assumptions you made in connection with performing your calculations as to how far the scope of 250 gallons of perc would spread?
A. Yes.
Q. Okay. Did you make any other assumptions?
MR. GROSSBART: Again, we're limiting the

Page 61

question to his conclusion of 48 feet diameter for 250 gallons, right?
MR. LYNCH: Yes.
MR. GROSSBART: Well, I object to the question because when you say any other assumptions besides what he's testified to and listed in his report, what are you asking him?
BY MR. LYNCH:
Q. Well, let's -- actually, if that helps, I'm not trying to trick you, if you want to go to your report, Exhibit 2A, first sentence, you also assume an intact level surface with which perc did not interact?
A. Right.
Q. Okay. Am I correct that would not be an asphalt pavement surface then?
A. That's correct.
Q. And why didn't you perform this calculation using an asphalt pavement surface?
A. There's not sufficient information to be able to calculate how far that would spill, that would spread.
Q. Is there sufficient information to approximate?
A. No, I don't believe so.
Q. Not to any reasonable degree of scientific certainty?
A. It would be a matter of tens of feet, you know, not 10 inches.

Page 62

Q. When you say it would be a matter of tens of feet?
A. The diameter of the spill would be a matter of tens of feet, not tens of inches.
Q. Under any circumstances?
A. No. None that I can think of. There is another assumption that's inherent in this, that's that the 250-gallon spill occurs instantaneously, it's all released all at once.
Q. So if somebody has a 250-gallon container and turns it over --
A. Yeah.
Q. -- actually above the level surface?
A. Right.
Q. Exhibit 3643, and I'll preface this by stating that math was never my strong suit, but it appears to me to contain several different calculations; is that correct?
A. Yes.
Q. Which of those calculations on that exhibit form the basis for any of the opinions expressed in your June 1st, 2009 report?
A. Only the first one on the breath of the spill, the diameter of the spill.
Q. And just so we're clear, that would be on the first page of the exhibit starting with calculations and

Page 63

then the formula that's directly above the portion of the page where it says maximum spill, it says death, but I assume that's depth?
A. Right. It's roughly the first two thirds of that first page, it concludes 24.1 feet is the spill radius.
MR. GROSSBART: Just so I'm clear, Bruce, is it everything above the heading maximum spill depth?
THE WITNESS: Yes, everything above the heading maximum spill depth.
BY MR. LYNCH:
Q. On this document, as we've alluded to, you then go on to perform a calculation that offers an amount for maximum spill depth; is that correct?
A. Yes.
Q. And that appears again on the first page of Exhibit 3643?
A. Yes.
Q. Will you be offering any testimony at trial -- strike that.
Does that calculation play any basis -- is that calculation a basis for any of the opinions expressed in your June 1st, 2009 report?
A. It underlies -- I'm not sure how to answer the

Page 64

question. Could you rephrase it, please?
Q. Yes. Are you relying on your calculation as to the maximum spill depth on Exhibit 3643, and your conclusion, I believe it's 3.3 inches, maximum depth, are you relying on that to support any of the opinions expressed in your June 1st, 2009 report?
A. The calculation shows that there was a lot of perc or a lot of stuff out there. It's not a thin film. If you have a spill of hundreds of gallons, it's going to cover a depth of a few inches, that's all that calculation intends to show.
Q. Is that a -- are the conclusions of that calculation something you will be testifying to at the trial of this matter?
A. No.
MR. GROSSBART: Are you talking about the 3.3 inches?
THE WITNESS: 3.3 inches, right.
A. Is that your question?
BY MR. LYNCH:
Q. Yes.
A. The 3.3 inches?
Q. Yes. Are you going to be offering any testimony in this matter as to what the depth of the spill of 250 to 1,000 gallons of perc would be?

Page 65

A. No.
Q. Not even what you just told me, that it would be a significant amount of 3 inches?
MR. GROSSBART: We reserve the right to use anything at trial that he's testified to today whether irrespective of his present intention, if he's testified to it. But I think you're missing the point of his last answer.
BY MR. LYNCH:
Q. Does the occurrence of any of the physical evidence you opine would result from this perc spill, as alleged in this litigation, depend on the depth of the perc that would result from the spill?
A. No.
Q. If you go to the next page of Exhibit 3643, at the top right-hand corner, it says page 2 of 3, the heading under Billings' matter is EPA evaporation rate. What are the calculations that follow that heading meant to show?
A. That's the evaporation rate from a perc spill on this type of a hypothetical surface under particular conditions of temperature and wind speed.
Q. And what temperature and wind speed did you assume for purposes of this calculation?
A. 77 degrees Fahrenheit ground temperature and air

temperature and the wind speed was 9.1 miles per hour.
Q. Would changing either of those variables affect the rate of evaporation?
MR. GROSSBART: The witness has already testified he's not giving evaporation testimony. We've stipulated that he's not giving evaporation testimony. His report doesn't deal with evaporation testimony. You're --
BY MR. LYNCH:
Q. Do any of --
MR. GROSSBART: You're just making -- you're just making life tougher for yourself, frankly because you're putting into the case and giving us, I suppose, an option for trial that we are trying to tell you you don't have to worry about. I mean, you can do what you want with the document, but --
MR. LYNCH: Let me jump in and --
MR. GROSSBART: -- this came up at a side bar. Do what you want, I mean, it's --
BY MR. LYNCH:
Q.. Opinion 1D on page 2 of your report.
A. Uh-huh.
Q. You state: That a spill of the type alleged in this litigation would result in perc odors noticeable over a large area. What's the basis for that opinion?

A. Basis for that opinion is that perc is volatile.
Q. Meaning it evaporates?
A. Meaning it evaporates.
Q. So does your calculation as to the evaporation rate of this spill provide part of the basis for that opinion?
A. No.
Q. Why not?
A. Because 250 to 1,000 gallons of perc would evaporate and would be -- it would be smelt over a large area -- it would be smelled over a large area. This is not a small spill we're talking about. We're talking about 5 to 20 drums of perc being released in a fairly short time, tons of perc being released in a short time.
Q. And just so I'm clear, that opinion is based generally on your knowledge that perc is volatile?
A. That's correct.
Q. Okay. It doesn't matter to your opinion how quickly or slowly the spill of perc as alleged in this litigation might have occurred? I'm sorry, how quickly or slowly the evaporation of the spill might have occurred?
A. 250 to 1,000 gallons of perc creates a very, very large spill that will be noticeable over a large area, because perc is volatile.
Q. Back in your opinion, opinion 2A, the second sentence

states a release of 1,000 gallons would spread to encompass a circle about 97 feet in diameter.
A. That's correct.
Q. Did you also -- is that conclusion also the result of a mathematical calculation?
A. Yes, it is.
Q. And am I correct that that particular calculation is not contained in Exhibit 3643?
A. That's correct.
Q. When did you perform that calculation?
A. I don't recall the exact date. This is almost four years ago now.
MR. LYNCH: We would ask that the witness give us his calculation for that conclusion as well.
MR. GROSSBART: Well, let me ask the witness, ask this voir dire question.
Dr. Dale, is the calculation for 97 feet in terms of format and assumptions used to make the calculations the same as set forth under 36 -- Exhibit 3643 except instead of assuming a 250-gallon spill, you assume a 1,000-gallon spill?
THE WITNESS: That's correct.
MR. GROSSBART: So the calculation methodology is the same?
THE WITNESS: That's correct.

MR. GROSSBART: Just substitute 1,000 for 250 in the calculation; is that right?
THE WITNESS: That's correct.
MR. LYNCH: Okay.
BY MR. LYNCH:
Q. And just so I'm clear then, on the 3643, if we look at the...
A. If you look under calculate spill radius, the heading calculate spill radius --
Q. Yeah.
A. -- then you see a term A subzero, and the next line you see an equals with a long line, you'll see 250 gallons written partway through that calculation. If you substitute 1,000 gallons in that, take the 1/4 root of the resulting number, you will get the result that I indicated.
Q. Okay. Actually it brings me to another point I want to clarify, this formula that you just discussed under the heading calculates spilled radius --
A. Yes.
Q. -- above that there is a statement that says one minute for spill to stop spreading?
A. Yes.
Q. Is that calculation something that forms the basis for any of the opinions expressed in your report, the rate

Page 70

at which the spill will spread?
A. No.
Q. Third sentence of opinion 2A, the diameter of releases of those quantities of perc onto asphalt would vary due to a number of factors including EG, slope and weather conditions. What other factors would cause variability in the diameter of the releases?
A. **Well, if it was released from a hose under a pump, the velocity of which it came out of that hose, any attempts to clean it up, the wind speed, I should write them down so I don't lose track. So slope and wind speed and temperature and velocity of discharge and the time, how long it took to discharge, whether the discharge was uphill or downhill. The physical condition of the asphalt which it discharged, for instance, if it were presence of ruts or holes or any other structures that it ran into. For instance if it discharged into -- onto a tire of the truck that it was hypothetically being released from, I mean, there's a very large number of variables.**
Q. Can you estimate with any reasonable -- without knowing those variables, can you estimate with any reasonable degree of scientific certainty what the extent of the spreading of the spill of the type alleged in this litigation would have been?

Page 71

A. **I would believe it would be tens of feet.**
Q. And how did you arrive at that figure?
A. **It's 250 to 1,000 gallons of stuff, it's going to spread out. It's not very viscous and it's quite dense; in other words, it flows easily and it has a lot of momentum to make it flow. It will spread out. I can't imagine a situation where you put 11 barrels of perc on top of each other and they stand in a diameter of a few feet. They're going to spread out. It's absurd, frankly, to think it won't spread out a lot.**
Q. In your report you say, your characterize it as substantial spreading; is that correct?
A. **That's right.**
Q. And you quantify that as tens of feet?
A. **Tens of feet.**
Q. So in your expert opinion -- is your expert opinion that the minimal amount of spreading would be 10 feet, 20 feet?
A. **Tens of feet. I can't be more precise than that.**
Q. And that would be the result no matter what any of the variables you just discussed that might impact this might be?
A. **Under any reasonable set of variables, it will spread out tens of feet.**

Page 72

MR. DAVIS: I mean, the variables are the volume which are using his barrel analogy 5 drums up to 20 drums roughly, right?
A. **(Witness nods head affirmatively.)**
BY MR. LYNCH:
Q. One of the variables you mentioned in opinion 2A is slope, how does that affect the spreading of the diameter of the spill?
A. **Depending on the direction of the discharge, it will have different -- it's a -- I can't answer your question without, I guess, more details, but what other variables do you want me to assume; in other words, the rate of discharge, the angle of the discharge, whether it was being pumped?**
Q. Would you agree that if there's a spill of -- let's assume your instantaneous spill that you assumed for the purpose of your calculations, if that occurred on a sloped surface, wouldn't the perc tend to flow downhill in the direction of the slope?
MR. GROSSBART: What is the slope you're positing in your hypothetical, please? Objection to the form of the question. What slope are you positing in your hypothetical? Just say I refuse to the tell you that.
MR. LYNCH: I'm not telling you that. I'm

Page 73

asking the witness. If you need -- if he needs --
MR. GROSSBART: Okay, that's fine. Just so it's clear, he's not giving you the slope, so go ahead and answer as best you can, Dr. Dale.
A. **Could you repeat the question, please?**
BY MR. LYNCH:
Q. Assuming your instantaneous spill of perc onto an asphalt surface --
MR. DAVIS: You want to know what effect an unknown slope --
BY MR. LYNCH:
Q. If there is a slope on that surface, isn't it true that the perc is going to tend to flow downhill in the direction of the slope?
MR. GROSSBART: Objection to the question.
A. **All fluids flow downhill. But there are other factors involved.**
BY MR. LYNCH:
Q. All other things being equal, is it correct that perc tends to flow further and faster than water?
A. **It tends to spread out further and faster than water does; an unconstrained flow of perc will spread out further and faster than water does, everything else being equal.**
Q. I would like you to assume a release of perc from a

Page 74

2-inch diameter hose, 60 gallons a minute, say at 2 percent slope on the asphalt pavement, the opening of the hose is pointing downhill, can you determine what the amount of surface area covered by that spill would be?
MR. GROSSBART: Objection to the incomplete nature of the hypothetical.
A. No, I can't.
BY MR. LYNCH:
Q. Can you determine it within a certain range?
A. Not without a lot more specific information like, for example, the temperature, the wind speed, the attempts to control it, the presence of other structures that might constrain the flow. Because perc is heavier than water, more dense than water and less viscous, when it's not channeled, when it's not in a pipe or a ditch or something, it will spread out further and faster than water.
Q. Would you agree that the release would tend to flow downhill in the direction of the slope?
MR. GROSSBART: Object to the incomplete nature of the hypothetical.
A. Are we talking about a hose releasing 60 gallons per minute still?
BY MR. LYNCH:

Page 75

Q. Uh-huh.
A. Fluids flow downhill.
Q. All right. Is there any way to calculate or determine -- let's back up.
Say the slope is downhill and that direction is north, is there any way to determine how much spreading of the perc there's going to be perpendicular to the slope, how much east/west spread?
A. This is a release of perc on asphalt?
Q. On asphalt.
MR. DAVIS: 60 gallons a minute?
MR. LYNCH: 60 gallons a minute.
MR. DAVIS: 2 percent slope still?
MR. LYNCH: 2 percent slope.
A. No.
BY MR. LYNCH:
Q. Any way to determine a range?
A. With the amount of information provided, I don't believe so.
Q. What if you assume 77 degrees, wind speed of 9.1 miles an hour?
A. No.
Q. Is that enough to even determine a range, whether it's 2 inches or 48 feet?
MR. DAVIS: Well, I'll object. That's

Page 76

being argumentative, he said it would be in tens of feet regardless, it will not be 2 inches.
A. I believe it will be tens of feet no matter what other circumstances.
BY MR. LYNCH:
Q. Even -- and as I understand it, even the east/west spreading as opposed to the amount, the distance it flows down the slope?
A. Yeah, I believe so.
Q. Okay. No circumstances, reasonable circumstances that you can envision where the east/west spreading of such a spill would not be tens of feet?
MR. GROSSBART: And you're assuming in your question no physical barriers to the spreading, right?
MR. LYNCH: Yes, yes.
MR. GROSSBART: Like structures?
MR. DAVIS: You've got a hose pumping out on a 2-percent slope?
MR. LYNCH: Yeah, and I can reset the assumptions.
MR. GROSSBART: The reason I raise that is because he had mentioned a variable would be whether the flow was constricted by physical structure. Now you're actually removing a variable as well as adding a variable, Chris, and that is why all these questions

Page 77

have been problematic, but -- and I have to keep interjecting.
If you have it in mind, Bruce, obviously you could and should answer the question.
A. I can't imagine any reasonable set of physical assumptions where the discharge of perc of 250 to 1,000 gallons on an asphalt surface wouldn't spread out tens of feet. I just can't imagine it.
BY MR. LYNCH:
Q. And I guess just so I'm clear, would spread out tens of feet in assuming no -- it doesn't run into contact with any physical barriers, tens of feet in every direction from the source of the spill?
A. No, not necessarily.
Q. Okay. So under certain circumstances if you have a spill of that amount of perc in the loading/unloading area, could it result in a flow of perc that is tens of feet in one direction, yet only 1 or 2 feet in the other direction, perpendicular direction?
MR. GROSSBART: Objection to the incomplete nature of the hypothetical.
A. There are far too many variables here to be able to give. I would need again, as I said before, to know the temperature, the wind speed, attempts to clean up the spill, whether there were potholes involved, any

Page 78

physical structures in the way. There's just -- there's a whole multitude of hypotheticals and as also the interaction of perc with the asphalt.
BY MR. LYNCH:
Q. Is there any way to calculate or estimate what the minimum surface area of that asphalt pavement to the loading/unloading area would have come into contact with perc from such a spill?
MR. DAVIS: Same objection.
MR. GROSSBART: Object to the incomplete nature, the woefully incomplete nature of the hypothetical.
A. My previous answer, reference my previous answer.
BY MR. LYNCH:
Q. And that's what I'm getting at, is I understand the hypotheticals are incomplete.
MR. GROSSBART: Thank you.
BY MR. LYNCH:
Q. Can you, without knowing all of the different variables that we've been discussing, can you offer an opinion with any reasonable degree of scientific certainty as to the area of asphalt that would have been covered by perc from a spill of the nature alleged in this litigation?
MR. GROSSBART: He told you it would be at

Page 79

least tens of feet.
A. It could cover a diameter of at least tens of feet.
BY MR. LYNCH:
Q. Tens of feet?
A. In my opinion, yes.
Q. I think that's part of my confusion, diameter, am I correct that that's a --
MR. GROSSBART: By the way, your expert stipulated to the same 48 feet.
BY MR. LYNCH:
Q. -- is a unit of measurement for circles; is that correct?
MR. DAVIS: We'll stipulate diameter is a reference to circles.
A. Okay, that's fine.
BY MR. LYNCH:
Q. Is the flow path necessarily going to be circular?
A. No.
Q. So if it's not circular, is there any way of --
A. To clarify then, the extent of spreading would be at least tens of feet.
Q. Okay. So at least in one direction it's going to go tens of feet?
A. Yes.
Q. It may go less in other directions?

Page 80

MR. DAVIS: Object, you mischaracterize, he said it would spread, which is more than one direction by definition.
BY MR. LYNCH:
Q. It will go tens of feet in all directions?
MR. GROSSBART: Still an incomplete hypothetical. A pencil line of spreading? Two pencil lines of spreading, a plume? You -- this is not proper questioning at all.
MR. LYNCH: The witness has testified that his definitions are --
MR. GROSSBART: Your questions are not proper.
MR. LYNCH: The witness has testified substantial spreading, and what does substantial spreading mean?
MR. GROSSBART: Well, you didn't ask that.
A. A spill of 250 to 1,000 gallons of perc would have spread tens of feet.
BY MR. LYNCH:
Q. In which -- in every direction?
A. No, in some directions.
Q. In some directions, but not necessarily other directions?
A. That's -- it's possible.

Page 81

Q. Is there any way of telling?
MR. GROSSBART: You have to posit the hypothetical. You're -- it's an improper question.
MR. LYNCH: The witness has testified in his report.
MR. GROSSBART: Chris, you --
MR. LYNCH: No, listen to me.
MR. GROSSBART: -- admitted it's an improper question.
MR. LYNCH: No, I haven't.
MR. GROSSBART: It's an incomplete hypothetical.
BY MR. LYNCH:
Q. How do you define substantial spreading?
A. Tens of feet.
Q. In which direction?
MR. GROSSBART: Objection to the incomplete nature of the hypothetical. I don't think you get it.
BY MR. LYNCH:
Q. You say substantial spreading, is that -- how do you define that, tens of feet in which direction?
MR. GROSSBART: His testimony...
A. Do you want to specify for me the temperature, the wind speed, the slope, the presence of potholes or ruts and the attempt of people, of anybody to clean it

Page 114

would fill a hemisphere that was I remember several thousand feet in diameter; in other words, it would fill a very large volume of air. This 250 gallons of perc at .005 percent in air fills a huge volume of air.
Q. So your opinion -- I'm confused. Your opinion that this would result in perc being noticeable over a large area is based on a calculation, the one you just alluded to?
MR. DAVIS: He did do a calculation prior to the last trial and I think he testified to it at the last trial. And I don't think that has changed.
A. Yeah, all I'm saying here is that it would be noticeable over a large area.
BY MR. LYNCH:
Q. How large of an area? Can you determine how large of an area without doing some type of a calculation?
A. It would be a very large area.
Q. Without doing a calculation, can you determine how large?
A. You mean how many cubic feet, how many miles in diameter, I mean...
Q. What do you mean by large area?
A. Well, certainly all over the Dyce site, the inhabited area of the Dyce site.

Page 115

Q. Can you --
A. Where people were working.
Q. Okay.
A. I'm -- I believe that that area would have been smelled by people working at the Dyce site.
Q. And what's the basis for that opinion?
A. 250 to 1,000 gallons of perc when evaporating would fill a very large volume of air.
Q. How large?
A. I'd have to do the calculation to know. I tried to give you an order of magnitude by telling you that it would fill a sphere thousands of feet on a site, a hemisphere actually, this is a huge amount of perc.
Q. I'm not trying to trick you and you're looking for the testimony?
MR. DAVIS: I've got his deposition, Chris.
MR. LYNCH: I've got the trial transcript, I think I do.
MR. DAVIS: I don't think he's blazing any new ground here that you haven't --
MR. LYNCH: I'm not, and I'm not suggesting it is. I just -- he had testified earlier that it's not --
MR. GROSSBART: Are you aware of a calculation in the record?

Page 116

MR. DAVIS: That's what I'm trying to find. I think there is one he testified to. It's my vague recollection that there is too.
MR. GROSSBART: Yeah, let's use the old calculation.
MR. DAVIS: I'm just looking at the deposition to see if I can find it.
MR. LYNCH: Let's mark this as --
MARKED FOR IDENTIFICATION:
DEPOSITION EXHIBIT 3662
1:20 p.m.
MR. GROSSBART: 3662. Is this the entire --
MR. LYNCH: All right. Exhibit 3662 I'll represent for the record is an excerpt from the trial transcript from the 2007 trial in this matter, just Dr. Dale's testimony.
MR. GROSSBART: It's complete as to Dr. Dale?
MR. LYNCH: Yes.
MR. GROSSBART: Could you just give us a minute off the record for a second?
MR. LYNCH: Certainly.
(Discussion off the record at 1:20 p.m.)
(Back on the record at 1:20 p.m.)

Page 117

MR. LYNCH: Basically I'm just trying --
MR. DAVIS: You want to go through his calculation --
MR. LYNCH: Yeah.
MR. DAVIS: -- behind his --
BY MR. LYNCH:
Q. Behind your opinion as to large.
MR. DAVIS: In the '09 report, I think. Go ahead and elaborate, Bruce.
A. The calculation -- what's the question I'm responding to?
BY MR. LYNCH:
Q. Is your opinion that --
MR. DAVIS: 2H.
BY MR. LYNCH:
Q. -- 2H in your report that the smell caused by release of 250 to 1,000 gallons of perc would be noticeable over a large area based on any mathematical calculation?
A. Yes, it is.
Q. Okay. And what is that calculation?
A. The calculation is the concentration of 50 parts per million at which people can smell perc, and the total for a 500-gallon spill, for a 500-gallon spill if all of that spill were converted to vapor, okay, in other

Page 118

words, all that 500 gallons became vapor, it would fill a hemisphere, a bowl, 250 parts per million and the bowl would be 1,000 feet in diameter, over 1,000 feet in diameter.
Q. So you would have 250 parts per million?
A. 50 parts per million.
Q. I'm sorry, 50 parts --
MR. DAVIS: Up to 50 million.
A. Yes.
BY MR. LYNCH:
Q. You would have up to 50 parts per million of perc in the atmosphere throughout that entire hemisphere based on your calculations; is that correct?
A. No, that's not what my calculation is saying.
Q. Please explain to me then.
A. What my calculation is saying is, if you took 500 gallons of perc and converted it all to vapor, and then you diluted that vapor to 50 parts per million, what's the total volume it would occupy, assuming that volume is spherical, but you restrict it from the ground, it's going to fill a hemisphere, a globe, okay, imagine the perc in the center evaporating and expanding to fill the globe. It will fill a globe of 1,000 feet in diameter, a very large distance.
Q. What's the formula you use for that calculation?

Page 119

A. The volume of the sphere, actually volume of a hemisphere, 4/3 pi r cubed.
Q. Do you need to make any assumptions -- strike that.
Do you need to make any assumptions as to the rate of evaporation of this spill?
A. I assume that it all evaporated instantaneously.
Q. If the spill did not all evaporate instantaneously, would that affect the area over which the odor would have been noticed?
A. Yes.
Q. How so?
A. Well, if it evaporated more slowly, it -- it may have spread less far initially, but it would have been present over a longer period of time. The more rapidly it evaporates, the more quickly it dissipates, the slower it evaporates, the more slowly it dissipates; in other words, it is noticeable over a longer period of time, but over a smaller area.
Q. Let's just stick with the area that would have been impacted, what other variables might affect the size of the area that would have -- that a perc spill of the magnitude alleged in this litigation would have been noticeable?
A. Primarily the rate of evaporation or the wind speed -- and wind, sorry, the amount varied of wind speed.

Page 120

Q. What factors affect the rate of evaporation?
A. Temperature, also wind speed, surface area exposed, how far spread out the spill is, attempts to clean it up.
Q. Did you make an assumption as to wind speed for purposes of your calculation?
A. No. You're referring to the calculation 2H?
Q. To the calculation you testified to on pages 1410 and 1411 of the trial transcript.
A. I assumed no wind speed at all.
Q. Okay. And how would wind speed affect your calculations?
A. What calculation are you referring to?
MR. DAVIS: You're talking about the diameter?
BY MR. LYNCH:
Q. The existence of this 1,000 foot diameter hemisphere or bowl for which this area would have been noticeable, if you assume there was at least some wind speed, how would that affect?
A. I would have to know the direction of wind speed, from where it was coming, the shading or the obstruction of the wind that was caused by the buildings, you know, once again, temperature.
Q. When you say large area for purposes of opinion 2H,

Page 121

can you quantify that, what's large?
A. Well, certainly over the area of the Dyce site where people work, I just can't imagine that people working there wouldn't smell 250 to 1,000 gallons of perc spilled if they're unloaded in that back area.
Q. Does your opinion make any assumptions one way or the other as to whether the entire amount of perc spilled stayed in the loading/unloading area?
A. No.
Q. So even if it didn't stay in the loading/unloading area, your opinion would be that the spill -- that the odor of the perc spill would have been noticeable over the entire working area of the site?
A. I can't imagine any reasonable circumstances under which a spill of that size wasn't noticeable.
Q. Is the calculation you performed on -- or discussed on pages 1410 and 1411 of the trial transcript, Exhibit 3662, the only calculation you performed in connection with this opinion?
MR. GROSSBART: When you say this opinion, you mean 2H?
MR. LYNCH: Yes.
BY MR. LYNCH:
Q. Well, the opinion as to the extent of the odor of this perc spill?

BILLINGS MATTER 12/11/05 PG 1/3

CALCULATIONS

ASSUME 250 GAL. SPILL + 77°F GROUND TEMP. (+ AIR TEMP)

$$t_{vs} = 0.02346 (g \rho V \mu / \sigma)$$

$$= 0.02346 \left(\frac{32.17\ ft}{sec^2} \right) \left(\frac{250\ gal}{} \frac{ft^3}{7.48\ gal} \right) \times \frac{101.1\ LB}{FT^3} \frac{0.75\ cp}{} \left(\frac{cm^2}{31.8\ Dyne} \right) \simeq \underline{60\ sec}$$

⇒ 1 minute for spill to stop spreading

Calculate spill radius

$$a_0 = 1.4131 (\sigma V t_{vs} / \mu)^{1/4}$$

$$= 1.41 \left[\frac{31.8\ DYNE}{CM^2} \frac{60\ sec}{} \left(\frac{250\ gal}{} \frac{FT^3}{7.48\ GAL} \right) \times \frac{}{0.75\ cp} \right]^{1/4} = \underline{24.1\ FT} = \text{spill radius (ft)}$$

MAXIMUM SPILL DEPTH

$$h_0^3 + 3a^2 h_0 - (6 V_0 / \pi) = 0$$

$$h_0^3 + 3(24.1)^2 h_0 - (6(250\ gal)/3.1416) = 0$$

$$h_0^3 + 1{,}739\ h_0 - 477.4 = 0$$

CUBIC SOLUTION → $h_0 = 0.275$ FT = 3.3 inches (maximum depth)

BILLINGS MATTER

EPA Evaporation rate

$$E = 0.28\, u^{0.78}\, M^{0.667}\, P_{vp,s} / RT_A$$

$$u = \frac{9.1 \text{ miles}}{\text{hour}} \bigg| \frac{\text{hr}}{60 \text{ min}} \bigg| \frac{5280 \text{ ft}}{\text{mile}} = \underline{\underline{800.8 \text{ FT/MI}}}$$

M = Molecular weight = lb/lmole = 165.8 lb/lb mole

$P_{vp,s}$ = 18.9 torr

R = ft^3 torr / lb mol - °R

T_A = 25°C = 77°F = 537°R = 298°K

E = (lb/ft^2-min]

$$\frac{0.28 \left(\frac{800.8 \text{ FT}}{\text{MIN}}\right)^{0.78} \left(\frac{165.8 \text{ lb}}{\text{lbmol}}\right)^{0.667}}{}$$

$$\times \frac{18.9 \text{ torr}}{} \bigg| \frac{}{537 \text{°R}} \bigg| \frac{\text{lbmol °R}}{0.7302 \text{ ft}^3\text{-}\cancel{\text{atm}}} \bigg| \frac{\text{atm}}{\cancel{760 \text{ torr}}}$$

$$= \frac{0.28 \mid 184.0 \mid 30.2 \mid 18.9}{537 \mid 0.7302 \mid 760}$$

≅ 0.10 lb/ft^2/min

spill area = $\pi \left(\frac{24.1 \text{ ft}}{}\right)^2$ = 1,825 ft^2

BILLINGS MATTER

TOTAL SPILL MASS

$$= \frac{250 \text{ gal}}{} \left| \frac{13.5 \text{ LB}}{\text{GAL}} \right. = 3{,}375.0 \text{ LB}$$

TIME TO EVAPORATE

$$\text{TIME} = \frac{3{,}375 \text{ LB}}{} \left| \frac{\text{FT}^2\text{-MIN}}{0.10 \text{ LB}} \right| \frac{}{1{,}825 \text{ FT}^2}$$

$$\boxed{= 18.5 \text{ MIN}}$$

Estimating Rates of Spreading and Evaporation of Volatile Liquids

John Barry
Contract Engineer,
DuPont Corp.

Follow these guidelines to calculate how fast a pool of spilled liquid will spread across a surface, evaporate and potentially form a flammable mixture with the air.

Despite operators' meticulous efforts to avoid spills during the handling of volatile liquids, accidents can, and do happen. In such cases, the ability to predict the rate at which the liquid spreads and how fast it evaporates prove invaluable. The former would be instrumental in planning and designing containment. The latter would be useful in finding the vapor concentration of the substance in ambient air, which would help one to determine the electrical area classification, fraction of lower explosive limit achieved, and address other similar safety-related issues. In this article, methodologies will be presented for calculating spill spreading and evaporation rates. Examples featuring these methods are used to find the liquid mass remaining at any given moment and the time required to evaporate the entire spill.

First, one must assume that: the volume of spilled liquid is known (*e.g.*, derived from batch data as the largest volume used in a process) or can be derived (*e.g.*, using the flowrate from a leak point and approximate duration of the leak); the liquid is well characterized in terms of density (ρ), surface tension (σ), viscosity (μ) and vapor pressure (P_{vp}); the liquid is at ambient temperature and barometric pressure, which are known; and the spill progresses as a liquid spreading across a smooth, level surface.

How far will a spill spread?

A liquid that is spilled on a flat surface will progress in three regimes *(1)*:

- the gravity-inertia regime, in which gravity tends to spread the fluid and is opposed by the inertia of the fluid
- the gravity-viscous regime, in which gravity tends to spread the fluid and is opposed by the viscosity of the fluid
- the viscous-surface tension regime, in which the liquid viscosity is opposed by the surface tension of the fluid.

Most volatile liquids have viscosities less than or close to that of water (~1 cP), and will enter the viscous-surface tension regime in a few seconds. Eq. 1 yields the time required to enter the viscous-surface tension regime:

$$t_{vs} = 0.023462(gV\rho\mu/\sigma) \quad (1)$$

where g is the gravitational constant (ft/s²), V is the spill volume (ft³), and ρ (lb/ft³), μ (cP) and σ (dyne/cm) are evaluated at the ambient temperature (T_A) or the temperature of the air above the liquid pool. With t_{vs} one can calculate the radius of the spill at zero time (a_0) (*i.e.*, at the onset of evaporation):

Nomenclature

a = radius of spill, or dimension defined in Eqs. 16 and Eq. 65, ft
A = area exposed to air, ft^2
b = collection of constants defined in Eq. 29, (ft/lb)$^{1/3}$
c = collection of constants defined in Eq. 32, (ft/lb)$^{1/3}$
D = diffusivity of solvent through air, ft^2/min
E_i = evaporative mass flux, lb/ft^2-min
g = gravitational constant, ft/s^2
Gr = Grashof number, dimensionless
h = depth of spherical cap at apex, ft^2
J = collection of constants, as defined in Eq. 61, lb$^{2/3}$/min
k = mass transfer coefficient, ft/min
L = characteristic length, ft
m = collection of constants, as defined in Eq. 78, ft/min
M = molecular weight, lb/lbmol
n = collection of constants, as defined in Eq. 77, lb$^{1/3}$/min
Nu = Nusselt number, dimensionless
Pr = Prandtl number, dimensionless
P_m = vapor pressure, torr
q = constant in mass flux equation, as defined in Eq. 65, lb$^{2/5}$/min
r = radius of spherical cap, ft
R = ideal gas constant, ft-lb/lbmol°R
R' = ideal gas constant, ft^3-torr/lbmol°R
Re = Reynolds number, dimensionless
Sc = Schmidt number, dimensionless
Sh = Sherwood number, dimensionless
t = time, min
T = temperature, °R
u = air velocity, ft/min
v = collection of constants, as defined in Eq. 56, ft-lb$^{1/4}$/min
V = volume of spill, gal or ft^3
W = mass of spill, lb
x = collection of constants, as defined in Eq. 66, ft-lb$^{1/15}$/min
y = collection of constants, as defined in Eq. 75, ft-lb$^{1/12}$/min
z = collection of constants, as defined in Eq. 74, lb$^{5/12}$/min

Greek symbols

α = complement of central half angle, rad
β = central half-angle of spherical cap, rad
μ = viscosity of liquid, cP or lb/ft-min
δ = concentration of evaporating species lb/ft^3
ρ = density of liquid, lb/ft^3
σ = surface tension of liquid, dyne/cm

Subscripts

A = ambient conditions
AB = movement from liquid to ambient air
cap = spherical cap
F = correction factor
H = hydrazine, reference substance for vapor pressure
l = laminar flow
p = pool of liquid
S = liquid under consideration
sph = spherical shape of spill
vs = viscous surface-tension regime
0 = initial conditions
1 = conditions after first time interval
2 = conditions after second time interval

$$a_0 = 1.413142(\sigma V t_{vs}/\mu)^{1/4} \quad (2)$$

What is the shape of the spill?

The shape of the volume of spilled liquid should be modeled in such a way as to enable the calculation of the area exposed to the atmosphere. In the real world, the spill assumes the shape of a spherical cap. If one determines the proportions of the spherical cap (and those of the corresponding hypothetical sphere), one can find the exposed surface area of the spill. The volume of a spherical cap is calculated as *(2)*:

$$V_{cap} = (\pi h/6)(3a^2 + h^2) \quad (3)$$

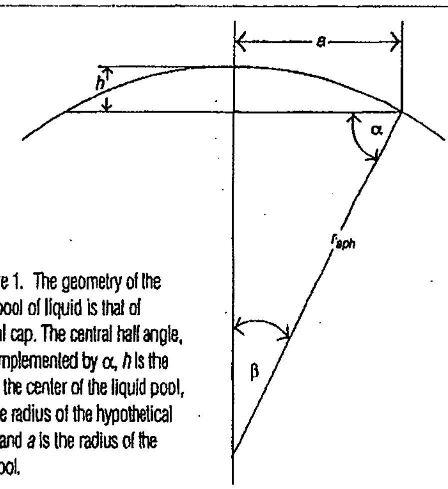
$$V_{cap} = (\pi h^2/3)(3r_{sph} - h) \quad (4)$$

where h is the depth of liquid at the center of the spill, a is the radius of the spill, and r_{sph} is the radius of the hypothetical sphere of which the cap is part. The initial radius of the spill (*i.e.*, the radius measured immediately following the brief interval t_{vs} after the liquid is first spilled) is noted as a_0. It is calculated with Eq. 2, where the volume of the spherical cap is V_0, and the time with respect to the evaporation process is zero. Note that during the spreading phase, no evaporation takes place.

Correspondingly, the height of the spherical cap at the center, h_0, the maximum depth of the spill, is calculated as:

$$h_0^3 + 3a^2h_0 - (6V_0/\pi) = 0 \quad (5)$$

This cubic equation can be solved analytically, or, more



■ Figure 1. The geometry of the spilled pool of liquid is that of spherical cap. The central half angle, β, is complemented by α, h is the depth at the center of the liquid pool, r_{sph} is the radius of the hypothetical sphere, and a is the radius of the liquid pool.

conveniently, by the use of a spreadsheet solver function. If one assumes that the central half angle (β) of the cap (Figure 1) remains constant during the course of the spill, then:

$$\sin\beta = a_0/r_0 \quad (6)$$

where r_0 is the initial radius of the spherical cap, and:

$$\tan\beta = h_0/a_0 \quad (7)$$

Then, substituting Eq. 7 into Eq. 5:

$$a_0^3\tan^3\beta + 3a_0^3\tan\beta - (6V_0/\pi) = 0 \quad (8)$$

A collection of terms leads to the expression:

$$\tan^3\beta + 3\tan\beta - (1/a_0^3)(6V_0/\pi) = 0 \quad (9)$$

Eq. 9 is a cubic equation and may be solved for tanβ using a spreadsheet. Readers seeking a rigorous solution should consult Ref. 3 and use the key words, "cubic equation."

With tanβ (and therefore β), h and a in hand, one can calculate the surface area of the cap using *(3)*:

$$A_{cap} = 2\pi r_{sph}h \quad (10)$$

Weisstein defines r_{sph} as *(2)*:

$$r_{sph}\sin\alpha = r - h \quad (11)$$

where α is the complement of β:

$$\alpha = \pi/2 - \beta \quad (12)$$

Other important relationships include:

$$r_{sph}\sin\beta = a \quad (13)$$

$$a\csc\beta = r_{sph} \quad (14)$$

$$h = a\tan\beta \quad (15)$$

$$a = h\cot\beta \quad (16)$$

These equations will come in handy when seeking a solving equation for h. It is now possible to write the unsteady-state mass balance on the spill, assuming that the evaporative mass flux (E) — or the evaporation rate, normalized over the area exposed to the environment — remains constant:

$$-dW/dt = -\rho dV_{cap}/dt \quad (17)$$

$$-dW/dt = EA_{cap} \quad (18)$$

$$-dW/dt = E(2\pi r_{sph}h) \quad (19)$$

Here, A_{cap} and V_{cap} are the surface area (ft^2) and volume (ft^3) of the spherical cap at any time t (min); W is liquid mass (lb); ρ is liquid density (lb/ft^3); E is mass flux (lb/ft^2-min); and r_{sph} and h are measured in ft. It is assumed that β is constant throughout the course of the spill. Eq. 4 may be rearranged to solve for r_{sph}:

$$r_{sph} = (1/3)(3V_{cap}/\pi h^2 + h) \quad (20)$$

Since $V_{cap} = W/\rho \quad (21)$

by substitution:

$$r_{sph} = (1/3)(3W/\pi\rho h^2 + h) \quad (22)$$

Substitution of Eq. 16 in Eq. 5 to define h yields:

$$h^3 + 3(h^2\cot^2\beta)h - 6V/\pi = 0 \quad (23)$$

$$h^3 + 3h^3\cot^2\beta - (6V/\pi) = 0 \quad (24)$$

Eq. 24 may be rewritten as:

$$h^3(1 + 3\cot^2\beta) = 6V/\pi \quad (25)$$

Taking the cubic root of both sides yields the following:

$$h = (6V/(\pi(1 + 3\cot^2\beta)))^{1/3} \quad (26)$$

$$h = (6W/(\pi\rho(1 + 3\cot^2\beta)))^{1/3} \quad (27)$$

$$h = bW^{1/3} \quad (28)$$

where:

$$b = (6W/(\pi\rho(1 + 3\cot^2\beta)))^{1/3} \quad (29)$$

Combining Eqs. 22 and 27, and performing extensive rearrangement and substitution leads to:

$$r_{sph} = (W^{1/3}/3)[(3(1 + 3\cot^2\beta)^2/4\pi\rho)^{1/3} + (6/\pi\rho(1 + 3\cot^2\beta))^{1/3}] \quad (30)$$

$$r_{sph} = cW^{1/3} \quad (31)$$

where:

$$c = 3(1 + 3\cot^2\beta)^2/4\pi\rho)^{1/3} + (6/\pi\rho(1 + 3\cot^2\beta))^{1/3} \quad (32)$$

The constants b and c are expressed in units of ft/lb$^{1/3}$ when English units are used. Subsequently, an expression for A_{cap} in terms of the mass of the liquid may be derived:

$$A_{cap} = 2\pi r_{sph}h \quad (33)$$

$$A_{cap} = 2\pi bcW^{2/3} \quad (34)$$

Eq. 34 is substituted into Eq. 18 to yield:

$$-dW/dt = E(2\pi bcW^{2/3}) \quad (35)$$

Rearranging Eq. 35 yields:

$$W^{-2/3}dW/dt = -(2\pi bc)E \quad (36)$$

Integration results in:

$$3W_1^{1/3} - 3W_2^{1/3} = 2\pi bcE(t_2 - t_1) \quad (37)$$

where W_1 and W_2 are the mass in the spill at times t_1 and t_2, respectively:

$$W_2 = (W_1^{1/3} - 2\pi bcE(t_2 - t_1)/3)^3 \quad (38)$$

If one assumes that β and E are constant, the cubic root of the mass in the spherical cap decreases linearly with time.

Determining the evaporative flux

There are three methods for estimating E. Two apply to a spill exposed to a moving air stream. The third method, Stiver-MacKay, can be extended to cover the case of a spill exposed to still air.

1. U.S. Air Force method. This empirical method is based on the evaporation of hydrazine at ambient temperatures (*4*). The evaporative flux for other liquids is estimated using the following equation, which is normalized for the effects of temperature and the properties of a liquid other than hydrazine:

$$E = 4.66 \times 10^{-6}u^{0.75}T_F M(P_{vp,S}/P_{vp,H}) \quad (39)$$

In the equation above, M is molecular weight (lb/lbmol), $P_{vp,S}$ and $P_{vp,H}$ are vapor pressures of the spilled substance and hydrazine respectively (torr) and T_F is a temperature correction factor defined conditionally as follows:

$$\text{When } T_P < 32°F,\ T_F = 1 \quad (40)$$

$$\text{When } T_P > 32°F,\ T_F = 1 + 0.00133(T_P - 32)^2 \quad (41)$$

In the original work, $P_{vp,S}$ and $P_{vp,H}$ are expressed in torr, but when using Eqs. 41 and 42, any consistent set of units is applicable, since the vapor pressure contribution is dimensionless. The original work also evaluates the vapor pressures at T_A. Although T_A is not equal to T_P, it is reasonable to assume they are equivalent, barring special situations (*e.g.*, a cold liquid spilled in a warm environment).

2. U.S. EPA method. Below is a slightly modified form of the empirical equation developed by the U.S. Environmental Protection Agency (EPA) to define evaporative flux (*5, 6*):

$$E = 0.28u^{0.78}M^{0.667}P_{vp,S}/RT_A \quad (42)$$

where u is the air velocity (ft/min) and $P_{vp,S}$ is expressed in units of torr, since the vapor-pressure contribution term is not dimensionless.

3. Method of Stiver-MacKay. This method employs a mass transfer coefficient explicitly. As such, it lends itself to situations other than that of a liquid pool exposed to a moving air stream (*7, 8, 9, 10*):

$$E = kP_{vp,S}M/R'T_{RA} \quad (43)$$

In this case, k is the mass transfer coefficient measured in ft/min or ft/s, and R' is the ideal gas constant measured in ft³torr/lbmol°R. One can define k using the following empirical relationships:

$$k = 0.00293u \text{ (ft/s)} \quad (44)$$

$$k = 0.1758u \text{ (ft/min)} \quad (45)$$

Beyond constant flux — forced convection

The derivations presented thus far are predicated on the assumption that the evaporative flux is independent of the geometry (and thus the characteristic dimension) of the spill. However, the mass-transfer coefficient — and therefore flux — is usually a function of some characteristic length of the geometry in question. E will vary with the changing geometry of the spill because, in the real world, there is usually movement of air above the spilled liquid. This creates a pressure differential, causing evaporative mass transfer to occur by forced convection. To account for the effects of forced convection, a mass-transfer coefficient that depends upon a characteristic dimension of the spill is introduced into the evaporative flux equation.

It is assumed here that the term "flow," except for the transient case of the spreading of the spilled liquid, refers to the air above the spill. Typically, the radius of curvature of the spill is sufficiently large such that the flow of air behaves like air flowing past a flat plate. This flow can be turbulent or laminar.

Bennett and Myers state that for flow past a flat plate, the laminar-to-turbulent transition occurs at about $Re \approx 3 \times 10^5$ (*11*), where Re is the Reynolds number calculated for a plate of length L as:

$$Re_L = u\rho L/\mu \quad (46)$$

L is a characteristic length of the geometry in question, and u, ρ and μ are the velocity, density and viscosity of the moving fluid, respectively. L takes the form of $2a$, where a is the radius of the spherical cap. The velocity is assumed to have been measured (*e.g.*, by a local

anemometer) or determined otherwise (*e.g.*, by a local weather report). The ρ and μ of air are obtained from tables of physical properties in a standard reference (*e.g.*, *Perry's Chemical Engineers' Handbook*).

Bennett and Myers show a dimensionless expression for the mass transfer coefficient for laminar flow using the Sherwood (Sh), Schmidt (Sc) numbers:

$$Sh = 0.66Re_L^{1/2}Sc^{1/3} \quad (47)$$

$$Sc = \nu/D_{AB} \quad (48)$$

$$Sc = \mu/\rho D_{AB} \quad (49)$$

$$Sh = kL/D_{AB} \quad (50)$$

where μ is liquid viscosity (lb/ft-min) and D_{AB} is the diffusivity of substance A diffusing through substance B (ft²/min) and may be found by the methods described by Reid, *et al.* *(12)*. Equating Eqs. 47 and 50, and solving for k:

$$k = 0.66(D_{AB}/L)Re_L^{1/2}Sc^{1/3} \quad (51)$$

$$k = 0.66(D_{AB}/L)(Lu\rho/\mu)^{1/2}(\mu/\rho D_{AB})^{1/3} \quad (52)$$

$$k = 0.66(D_{AB}/L^{1/2})(u\rho/\mu)^{1/2}(\mu/\rho D_{AB})^{1/3} = \quad (53)$$

$$k = (2a)^{-1/2}(0.66D_{AB}^{2/3}u^{1/2}(\rho/\mu)^{1/6}) \quad (54)$$

The characteristic dimension a can be expressed in terms of the mass of the spherical cap using a combination of Eqs. 16 and 28:

$$a = b\cot\beta W^{1/3} \quad (55)$$

Thus,

$$k = W^{-1/6}(2b\cot\beta)^{-1/2}D_{AB}^{2/3}u^{1/2}(\rho/\mu)^{1/6} \quad (56)$$

$$k = \nu W^{-1/6} \quad (57)$$

Solving for ν yields:

$$\nu = D_{AB}^{2/3}(u/2b\cot\beta)^{1/2}(\rho/\mu)^{1/6} \quad (58)$$

The result of substituting Eq. 57 in the Stiver-MacKay relationship for flux yields:

$$E = \nu P_{vp,S}M/R'T_A W^{-1/6} \quad (59)$$

Use of Eq. 59 in the unsteady-state mass balance, followed by integration, results in this empirical equation for forced-convection evaporative mass flux in the laminar flow regime:

$$W_1^{1/2} - W_2^{1/2} = j(t_2 - t_1), \quad (60)$$

where:

$$j = 2\pi bc\nu P_{vp,S}M/R'T_{RA} \quad (61)$$

Thus, for laminar flow, when accounting for a change in the mass transfer coefficient (and therefore E) as a function of the changing dimensions of the liquid pool, the square root of W decreases linearly with time.

In many standard texts *(11)*, the analogy between heat and mass transfer developed originally by Chilton and Colburn is used to derive mass-transfer relationships for known geometries and flow conditions based on dimensionless-numbers for heat transfer.

As a corollary, if one has a relation for heat transfer for a given geometry (*e.g.*, flow past a flat plate), then by analogy, one has a relation for mass transfer for that same geometry. For turbulent flow, this analogy between heat and mass transfer is used to find E. For heat transfer involving turbulent flow past a flat plate, Bennett and Myers give this correlation for the Nusselt number *(13)*:

$$Nu = 0.0365Re^{4/5}Pr^{1/2} \quad (62)$$

The exponent on the Prandtl number (Pr) is open to some debate. Based on other work *(14)*, an exponent of 1/2 is used here. Thus, the mass-transfer analog is assumed to be:

$$Sh = 0.0365Re^{4/5}Sc^{1/2} \quad (63)$$

Eq. 63 is equated with Eq. 50 to solve for k. As for laminar flow, subsequent expressions for k are derived and substituted into the solving equation for E in the Stiver-MacKay relationship. The integration of the unsteady-state mass balance yields the following equation for turbulent convection:

$$W_2 = (W_1^{2/5} - 2q(t_2 - t_1)/5)^{5/2} \quad (64)$$

where q and x are constants, defined as:

$$q = 2\pi bcxP_{vp,S}M/R'T_A \quad (65)$$

$$x = 0.0365D_{AB}^{1/2}u^{4/3}(\rho/\mu)^{1/10}(2b\cot\beta)^{-1/3} \quad (66)$$

In the equations defining q and x, constants b and c are calculated as per Eqs. 29 and 32, respectively.

Extending the method to free convection

Next, the evaporative flux is examined under the conditions of free convection. The air above the pool is assumed to be completely still, and the driving force for mass transfer is the difference in concentration of the volatile compound between the liquid pool and the air above the pool.

To adapt the method explained for forced convection to the case of free convection, one needs a free-convection mass-transfer coefficient, which is again derived using the Chilton and Colburn analogy between heat and mass transfer, as applied to free convection past a flat plate of liquid.

For free convection in the laminar flow regime (*i.e.*, when $10^5 \leq Gr_L Pr \leq 2 \times 10^7$, where Gr is the dimensionless Grashof number for laminar flow), the heat transfer coefficient may be expressed as:

$$Nu = 0.54(Gr_L Pr)^{1/4} \tag{67}$$

and, for free convection in the turbulent flow regime: (*i.e.*, when $2 \times 10^7 \leq Gr_L Pr < 3 \times 10^{10}$):

$$Nu = 0.14(Gr_L Pr)^{1/3} \tag{68}$$

Using the Chilton and Colburn analogy, the mass transfer coefficient for free convection in the laminar flow regime: (*i.e.*, when $10^5 \leq Gr_{AB}Sc \leq 2 \times 10^7$) is:

$$Sh = 0.54(Gr_{AB}Sc)^{1/4} \tag{69}$$

and, for free convection in the turbulent flow regime (*i.e.*, when $2 \times 10^7 \leq Gr_{AB}Sc < 3 \times 10^{10}$) is:

$$Sh = 0.14(Gr_{AB}Sc)^{1/3} \tag{70}$$

In the equations above, Gr and Sc are defined as *(15)*:

$$Gr_{AB} = L^3 \rho g \Delta\rho_A/\mu^2 \tag{71}$$

$$Sc = \mu/\rho D_{AB} \tag{72}$$

For the purposes of this article, $L = 2a$. In addition, $\Delta\delta$ refers to the difference in concentration of the evaporating species between the boundary layer of liquid and the bulk fluid above it. Usually, the concentration of the evaporating species in the bulk fluid is zero or effectively zero.

Following a procedure similar to that used previously, one obtains for laminar flow:

$$W_2 = (W_1^{5/12} - (12z/5)(t_2 - t_1))^{12/5} \tag{73}$$

where:

$$z = 2\pi bcyP_{vp,S}M/R'T_A \tag{74}$$

$$y = 0.54((D_{AB})^3 g\Delta\delta/bc\cot\beta\mu)^{1/4} \tag{75}$$

Follow the procedure used for laminar flow to assess turbulent free convection:

$$W_2^{1/3} = (W_1^{1/3} - (n/3)(t_2 - t_1))^3 \tag{76}$$

where:

$$n = (2\pi bcmP_{vp,S}M/R'T_A) \tag{77}$$

and:

$$m = 0.14(D_{AB})^{2/3}(g\Delta\delta/\mu)^{1/3} \tag{78}$$

Rarely is the outdoor atmosphere completely still for any appreciable period of time. Therefore, for spills that occur under the condition of light winds to calm air, it is suggested that the estimated time for evaporation is calculated based on the average of the forced convection and free convection cases, since the actual situation lies somewhere between these two extremes. Furthermore, the upper limit on the product of the Gr and Sc numbers may limit the applicability of this analysis to small spills.

Example problems

Physical and transport properties, where required, are calculated from empirical correlations given by Yaws *(16)*.

Example 1. Assume 50 gal of methanol spills onto a level surface outdoors. A local thermometer reads $T_A = 59°F$, and a local anemometer gives an average wind speed of $u = 5$ mi/h. Estimate the greatest depth of the spill (h) and the time it will take the spill to evaporate ($t_2 - t_1$).

Summarize the known conditions and the physical properties of methanol: $P_{vp} = 69.058$ mmHg, $M = 32.044$ lb/lbmol, $W = 332.24$ lb, $\bar{R} = 555$ mmHg-ft³/lbmol°R, $\mu = 0.619$ cP, $\sigma = 24.869$ dyne/cm, $\rho = 49.707$ lb/ft³, and D_{AB} = lb/ft.

As a first pass, assume that the evaporative flux is independent of the dimensions of the spill (*i.e.*, E remains constant during the evaporation process). A preview of the calculations reveals that the EPA method yields the shortest evaporation time, while the Stiver-MacKay method yields the longest evaporation time. Therefore, for a conservative estimate, the Stiver-MacKay method will be used.

Calculate the initial spreading time, t_{vs}, using Eq. 1:

$t_{vs} = 0.023462[(32.174 \text{ ft/s}^2)(50 \text{ gal} \times 7.48 \text{ gal/ft}^3)$ $(49.707 \text{ lb/ft}^3)(0.619 \text{ lb/ft-s})/24.869 \text{ dyne/cm}] = 6.24$ s.

Calculate the pool radius at t_{vs} using Eq. 23:

$a_0 = 1.413142 [(24.869 \text{ dyne/cm})(6.684 \text{ ft}^3)(6.243 \text{ s})/(0.619 \text{ cP})]^{1/4} = 9.04$ ft.

In this calculation, the unit conversion factors for μ and σ have been worked into the coefficient. The liquid pool is assumed to take the form of a spherical cap, due to the effects of surface tension. Given the volume and the radius at time zero, solve Eq. 5 for the maximum depth of the pool at its center:

$h^3 + 3(9.04 \text{ ft})^2 h = 6V_0/\pi = 6(50 \text{ gal}/(7.48 \text{ gal/ft}^3))/\pi =$

12.77 ft³; therefore, $h = 0.052$ ft

β is found by rearranging Eq. 9 and using a spreadsheet solver function:

$\tan^3\beta + 3\tan\beta = (1/a_0^3)(6V_0/\pi)$. Thus, $\tan\beta = 0.005755$ rad, and $\beta = 0.00576$.

Per Eqs. 43 and 45:

$E = 0.1758(5$ mi/h$)(69.058$ mmHg$)(32.044$ lb/lbmol$)$ / $((555$ mmHg-ft³/lbmol°R$)(59 + 453.49$°R$))$ $= 6.76 \times 10^{-3}$ lb/ft²min.

Use this result in Eq. 37 to find the evaporation time, $t_2 - t_1$. Solve for t_2 with $t_1 = 0$ and $W_2 = 0$. This leads to:

$$t_2 = 3W_1^{1/3}/2\pi bcE$$

where:

$$b = (6W/(\pi\rho(1 + 3\cot^2\beta)))^{1/3} = 7.51 \times 10^{-3} \text{ ft/lb}^{1/3}$$

and

$$c = (3(1 + 3\cot^2\beta)^2/4\pi\rho)^{1/3} + (6/(\pi\rho(1 + 3\cot^2\beta)))^{1/3} = 113.42 \text{ ft/lb}^{1/3}.$$

Thus:

$$t_2 = 3(332.24 \text{ lb})^{1/3} / (2 \times 3.14 \times (7.51 \times 10^{-3} \text{ ft/lb}^{1/3}) \times (113.42 \text{ ft/lb}^{1/3})(6.76 \times 10^{-3} \text{ lb/ft}^2\text{min})) = 574.17 \text{ min}.$$

Example 2. Repeat Example 1, but this time, assume that the evaporative flux is a function of the pool radius (a_0) under conditions of forced convection. Since the flux varies throughout the evaporation process., one needs an integrated mass balance that accounts for the effect of the pool's shrinkage on the flux. The Stiver-MacKay method is the only one that includes an explicit term for k, and will be used to perform the calculations. All of the physical properties and constants (*e.g.*, b and c) are consistent with those cited in Example 1.

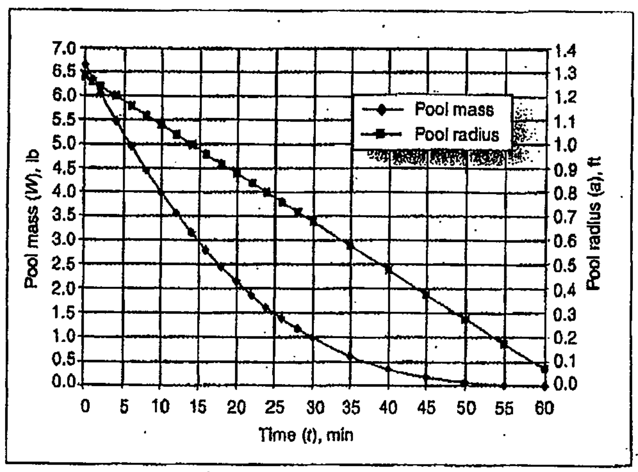
First, determine whether convection is turbulent or laminar using Eq. 46:

$$Re = (5 \text{ mi/h})(5{,}280 \text{ ft/mi})(0.076 \text{ lb/ft}^3)(2 \times 9.04 \text{ ft}) / ((0.018 \text{ cP})(2.419 \text{ lb/ft-h})/\text{cP}) = 8.33 \times 10^5.$$

Since Re is greater than 3×10^5, flow is turbulent and Eq. 64 should be used. This equation requires the determination of several constants. D_{AB} is determined using physical property estimation methods described in Ref. 12, 11-4.4

Table. Spill mass and volume vs. time under conditions of turbulent free convection.

Time (t), min	Mass of Spill (W_2), lb	Volume of Spill (V), ft³	Radius of Spill (a), ft
0	6.64	1.337E-01	1.28
1	6.34	1.275E-01	1.26
2	6.04	1.215E-01	1.24
4	5.47	1.100E-01	1.20
6	4.94	9.930E-02	1.16
8	4.44	8.931E-02	1.12
10	3.98	8.002E-02	1.08
12	3.55	7.139E-02	1.04
14	3.15	6.340E-02	1.00
16	2.79	5.604E-02	0.96
18	2.45	4.927E-02	0.92
20	2.14	4.306E-02	0.88
22	1.86	3.740E-02	0.84
24	1.60	3.226E-02	0.80
26	1.37	2.762E-02	0.76
28	1.17	2.344E-02	0.72
30	0.98	1.971E-02	0.68
35	0.60	1.215E-02	0.57
40	0.34	6.827E-03	0.47
45	0.17	3.342E-03	0.37
50	0.06	1.306E-03	0.27
55	0.02	3.300E-04	0.17
60	0.00	2.415E-05	0.07



■ Figure 2. Pool radius and liquid mass remaining as a function of time for the case of free convection in the turbulent flow regime.

Literature Cited

1. Putorti, A. D., *et al.*, "Flammable and Combustible Liquid Spill/Burn Patterns," U.S. Dept. of Justice; Office of Justice Programs, National Institute of Justice Report 604-00, Washington, DC (2001).
2. Weisstein, E., "Spherical Cap," http://mathworld.wolfram.com/ SphericalCap.html.
3. Jeffrey, A., *Handbook of Mathematical Formulas and Integrals*, Academic Press, §0.8, San Diego, CA (1995).
4. U.S. Environmental Protection Agency (EPA), Federal Emergency Management Agency (FEMA) and U.S. Dept. of Transportation, *Handbook of Chemical Hazard Analysis Procedures*, Washington, DC (1989).
5. U.S. EPA and U.S. FEMA, "Technical Guidance For Hazards Analysis," Equation 7, Section G-2, Appendix G, Washington, DC (Dec. 1987); www.epa.gov/swercepp/pubs/tech.pdf.
6. U.S. EPA, "Risk Management Program Guidance For Offsite Consequence Analysis," publication EPA-550-B-99-009, Section D.2.3, Appendix D, Equation D-1, Washington, DC (Apr. 1999); www.epa.gov/ceppo/pubs/oca/oca-all.pdf.
7. Stiver, W., and D. MacKay, "A Spill Hazard Ranking System For Chemicals," Environment Canada First Technical Spills Seminar, Toronto, Canada (1993).
8. Clewell, H. J., "A Simple Method For Estimating the Source Strength of Spills of Toxic Liquids," Energy Systems Laboratory, ESL-TR-83-03, available at Air Force Weather Technical Library, Asheville, NC (1983).
9. Ille, G., and C. Springer, "The Evaporation and Dispersion of Hydrazine Propellants from Ground Spills," Civil and Environmental Engineering Development Office, CEEDO 712-78-30; available at Air Force Weather Technical Library, Asheville, NC (1978).
10. Kahler, P., *et al.*, "Calculating Toxic Corridors," Air Force Weather Service, AWS TR-80/003, 1980; available at Air Force Weather Technical Library, Asheville, NC (1980).
11. Bennett, C. O., and J. E. Myers, "Momentum, Heat, and Mass Transfer," 2nd Ed., McGraw-Hill, New York (1974).
12. Reid, Robert C., *et al.*, *The Properties of Gases and Liquids*, 4th Ed., McGraw-Hill, New York (1987).
13. Bennett, C. O., and J. E. Myers, Equations 23–51, p. 367.
14. Hanna, O. T., and J. E. Myers, Engineering Experiment Station, Bulletin No. 148, Purdue Univ. (1962).
15. www.svce.ac.in/~msubbu/LectureNotes/MassTransfer/MT-2.htm, Eq. 4.30.
16. Yaws, Carl L., *Chemical Properties Handbook*, McGraw-Hill, New York (1999).

JOHN BARRY is a lead process engineer, currently working under contract for DuPont Corp. at the Chambers Works site in Deepwater, NJ (Phone: (856) 540-2364; Fax: (856) 540-3080; E-mail: john.barry.engr@comcast.net). Prior to consulting with DuPont, Barry was a contract process engineer at Jacobs Engineering's Premcor refinery (Delaware City, DE) and a lead process engineer for CDI Engineering (Philadelphia, PA). Barry received a BS in chemistry from the Univ. of Delaware and a MS in chemical engineering from the Univ. of Maryland. He is a licensed professional engineer in the states of DE and NJ, and is a member of AIChE.

and Table 11-1 to be 0.160 cm²/s = 0.010 ft²/min. The central half-angle is calculated as β = 0.00576 rad. Also, per Eq. 66:

$$x = 0.0365((0.010\ \text{ft}^2/\text{min})^{1/2})((5\ \text{mi/h} \times 88\ \text{ft/min/(mi/h)})^{4/3}(0.619\ \text{cP}(0.04032\ \text{lb/ft min/cP}))^{1/10}(2(7.51 \times 10^{-3}\ \text{ft/lb}^{1/3})\cot(0.00576\ \text{rad}))^{-1/3} = 11.62\ \text{ft-lb}^{1/15}/\text{min}.$$

And, per Eq. 65:

$$q = 2\pi bcxP_{vp,S}M/R'T_A = 2\pi(7.51 \times 10^{-3}\ \text{ft/lb}^{1/3}) \times (113.42\ \text{ft/lb}^{1/3})(11.62\ \text{ft-lb}^{1/15}/\text{min})(69.058\ \text{mmHg}) \times (32.0422\ \text{lb/lbmol})/((555\ \text{mmHg-ft}^3/\text{lbmol°R})(59 + 453.49°\text{R})) = 0.484\ \text{lb}^{2/5}/\text{min}.$$

Assume $W_2 = 0$ and $t_1 = 0$, and solve for t_2 using Eq. 64, which is rearranged as:

$$t_2 = 5W_1^{2/5}/2q = 5 \times (332.24\ \text{lb})^{2/5}/(2 \times 0.484) = 52.68\ \text{min}.$$

As may be expected, the predicted time required to evaporate the entire spill decreases significantly when one accounts for a change in the evaporative flux with the decreasing size of the pool.

Example 3. Consider a smaller spill (V_0 = 5 gal) of methanol. Once again, assume that the evaporative flux varies during the evaporation process. Assume that $u = 0$ ft/s and thus, only free convection takes place. Also, assume that the air above the spill contains a negligible concentration of vapor. Calculate the amount of time it will take to evaporate the entire spill.

The Stiver-MacKay method will be used because it includes an explicit term for k. This case exhibits turbulent flow free convection, since $ScGr = \sim 3.9 \times 10^9$. Thus, Eq. 76 is used with $W_2 = 0$ and $t_1 = 0$ to calculate t_2:

$$t_2 = 3W_1^{1/3}/n$$

where:

$$n = 2\pi bcmP_{vp,S}M/R'T_A = 0.0887\ (\text{lb/min})^{1/3}$$

$$m = 0.14(D_{AB})^{2/3}(g\Delta\delta/\mu)^{1/3} = 7.93\ \text{ft/min}.$$

Thus, t_2 = 63.6 min.

Example 4. Building on Example 3, in which the evaporative flux varies, calculate the mass of liquid remaining, along with the volume and radius of the spill, as evaporation progresses, until all of the liquid is evaporated.

Use Eq. 76 to solve for W_2 with $t_1 = 0$ and t_2 varying from 1 min to 60 min. To solve for a, find V using W_2/ρ. Then, using Eq. 2, solve for a. The results are shown in the Table and Figure 2. CEP